USE OF SERIES CAPACITORS FOR VOLTAGE REGULATION

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SUMMARY

This bulletin contains a discussion on the use of series capacitors as voltage regulators. Methods of calculating capacitor ratings and suggestions for their installation and protection are included.

USE OF SERIES CAPACITORS
FOR VOLTAGE REGULATION

The series capacitor is a current operated device which responds only to the current flowing through it. Since it is insensible to system voltage fluctuation originating between it and the power source, it can be used as a voltage regulator which responds automatically and instantaneously to variations in load current. It can, therefore, be used to reduce flicker difficulties due to motor starting.

It has the additional advantage of producing voltage correction proportional to the load current beyond the capacitor without the necessity of mechanically-driven controls. When properly applied it can, therefore, in many cases provide a simple and practically maintenance-free method of voltage regulation. Such an installation will compensate equally well for voltage drops due to inductive loads, or voltage rise due to leading power factors. This latter condition is a phenomenon almost unique with rural systems and frequently encountered under light load conditions. However, since introduction of a series capacitor has the effect of changing circuit constants and may in some cases cause "hunting" of synchronous machines or self-excitation of induction motors, proposed applications should be carefully checked as to the type of load which will draw current through the capacitor and possible effects of the installation.

Series capacitors may also be used in conjunction with induction regulators to provide closer regulation on selected portions of the system.

I. THEORY OF OPERATION.

A capacitor placed in series with the line introduces a negative reactance which compensates partially or wholly for the inductive (positive) reactance of the line. The product of load current and the reactance of the line results in a voltage drop which increases as the power factor of the load decreases (lagging) and the series capacitor will thus automatically compensate for this drop. During conditions of leading power factor the series capacitor will "buck" the voltage rise caused by the leading current flowing through the line reactance. (See equation 8 of the Appendix.) The size of the capacitor can be chosen so that its reactance exactly equals the inductive reactance of the line, thereby producing approximately the same effect as though the line contained resistance alone. If the capacitor is chosen so that its reactance is greater than the reactance of the line between its location and the power source, "over-compensation" of the line reactance occurs, thus balancing out not only the reactive drop or rise of the line between the source and the capacitor, but also all or part of the line resistance drop. In all cases, variation of the power factor over the load curve must be taken into account to prevent excessive voltage rise or drop at the capacitor location under certain combinations of load and power factor.

II. SYSTEM ANALYSIS PRIOR TO INSTALLATION OF SERIES CAPACITORS

A. Information Required

When analyzing a system prior to installation of series capacitors, the following information should be on hand:

1. A map of the system showing:

   (a) Transformer sizes and reactances of large transformers
   (b) Wire sizes, lengths and phasing
   (c) Distributed and large concentrated loads under peak and light load conditions

2. Data on loads with high peaks of short duration:

   (a) Maximum kva
   (b) Power factor at peak current

3. Maximum system peak kva

4. Normal system demand

5. Type and location of existing voltage regulators

6. Voltage drop study of the system at full and light loads

7. Power factor of system at full load and at light load

B. Voltage Gradient of System

Plot a diagram similar to Fig. 1, showing the voltage gradient along the system under consideration for full load and for light load periods.

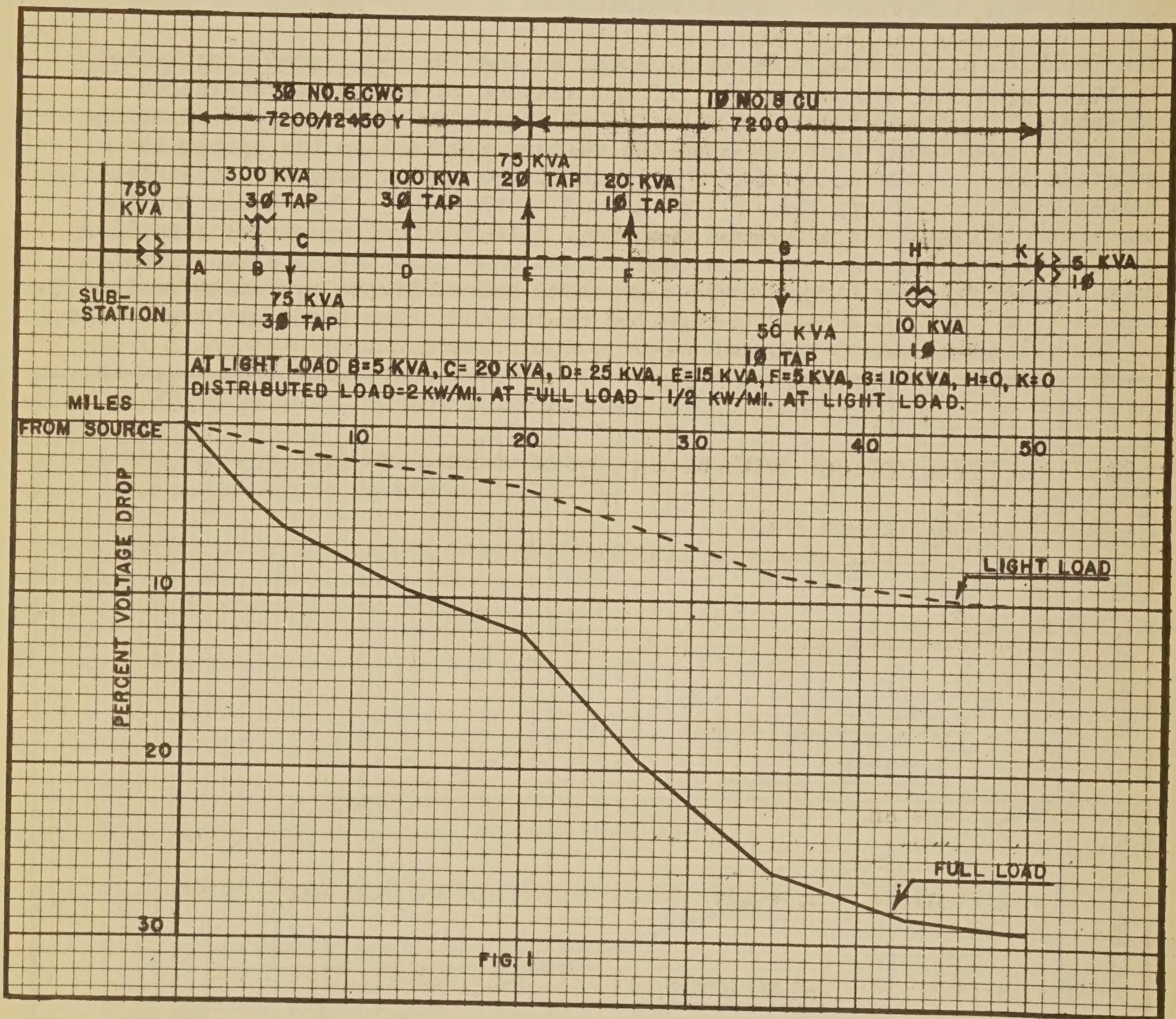

FIG. 1

"Percent voltage drop" is the ratio of voltage drop at any point to voltage at the source, expressed in percent.

"Percent voltage variation" is the difference between percent voltage drop at full load and at light load periods at any point.

"Percent regulation" is the ratio of the voltage difference at any point between no load and full load on the system, to the full load voltage at the same point, expressed in percent.

C. Determine Location of Series Capacitor

The location of the capacitor will depend on what is considered acceptable voltage variation on the system. If 10% voltage variation is considered acceptable, it is obvious from Fig. 1 that regulation must be applied to the system at some point near E. When the voltage gradient on the system is constant it is recommended that the capacitor be placed one-third the electrical distance between the source and end of the line. This would provide the best regulation as illustrated in Fig. 2, where the capacitor is applied so that the drop or rise at no point exceeds one-third the total uncorrected drop. However, when large loads or taps are taken off the system at various points, the location must be determined by cut and try methods with reference to the voltage gradient diagram.

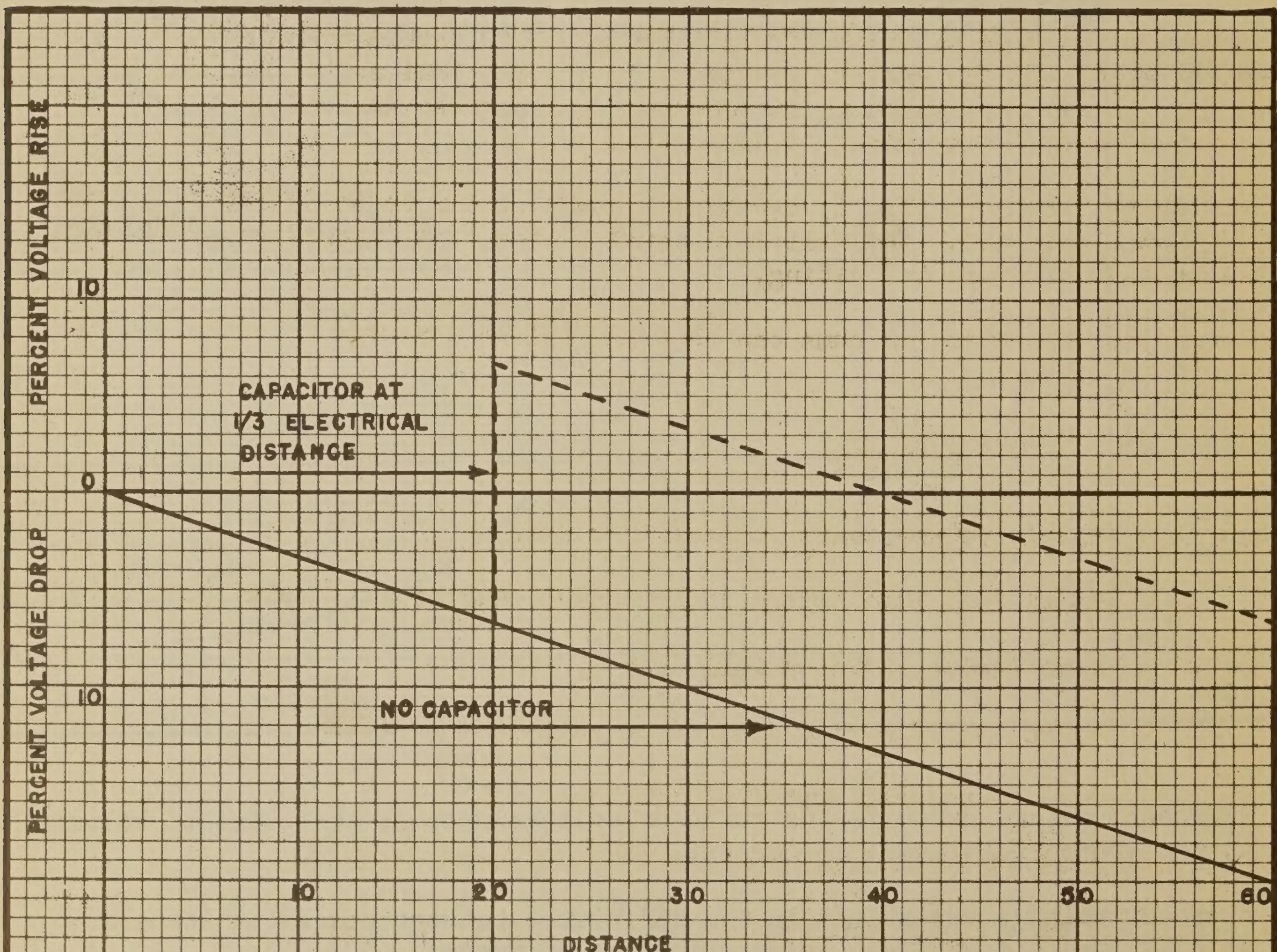

FIG. 2

In the system shown in Fig. 1, in order to limit the variation to 10% at K it would be necessary to decrease the full load voltage drop by about 10%.

A first choice for the capacitor location might be some point between E, where the variation approaches the 10% limit, and the end of the line. When this point has been decided upon, the reactance of the capacitor should be determined as outlined in the following section. Then, the voltage rise at light load at the capacitor should be calculated and another voltage gradient diagram drawn showing the variation with the capacitor in the circuit.

D. Calculation of Capacitor Rating

Series capacitors are rated by specifying the capacitive reactance in ohms, the line-to-ground voltage and the terminal-to-terminal voltage ratings. For determination of voltage ratings see III.

The capacitive reactance required will depend on the power factor and size of the load. For a given load, the lower the power factor (lagging), the smaller the capacitive reactance required to provide a given correction. Therefore, the capacitor rating should be based on the greatest load and the lowest (lagging) power factor, which conditions will usually occur at the same time. If these two conditions do not occur at the same time, a check should be made at various points to see which combination provides the greatest rise. If the ratings are based on a light load and high power factor, the voltage rise which would accompany an increase in load or a lowering of the power factor might be excessive.

In the system shown in Fig. 1, assume the power factor to be 75% at full load and 90% at light load. The full load power factor will, therefore, determine the selection of capacitor rating.

The capacitor reactance in ohms can be found by the formula:

$$* X_C = \frac{10 E^2 V}{K_L \sin \theta} \qquad (1)$$

where X_C = capacitive reactance in ohms (per phase)

K_L = kva at full load beyond the proposed capacitor location (per phase)

θ = power factor angle at full load

V = percent voltage rise desired at capacitor location

E = phase to neutral system kilovolts

The percent rise at light load (V_N) can then be found from:

$$V_N = \frac{K_{LN} X_C \sin \theta_N}{10 E^2} \qquad (2)$$

* For derivation of the formula see appendix.

where K_{LN} = load kva per phase beyond proposed capacitor installation at light load

θ_N = power factor angle at light load

E. Example

Referring to Fig. 1:

Assume the location of the capacitor at point E, with full load power factor of 75% and light load power factor of 90%.

Then: $K_L = 145$ kva

$\theta = \text{arc cos } 0.75 = 41.4$ degrees
$\text{Sin } \theta = 0.66$
$V = 10\%$
$\theta_N = \text{arc cos } 0.9 = 26.2$ degrees

$\text{Sin } \theta_N = 0.44$

$E = 7.2$ kilovolts
$K_{LN} = 30$ kva

$$X_C = \frac{10\,E^2 V}{K_L \sin\theta} = \frac{10 \times 7.2^2 \times 10}{145 \times 0.66} = 54 \text{ ohms}$$

$$V_N = \frac{K_{LN}\, X_C \sin\theta_N}{10\,E^2} = \frac{30 \times 54 \times 0.44}{10 \times 7.2^2} = 0.8\%$$

Thus in order to provide the desired voltage rise at full load, for the tap EK (Fig. 1) it will be necessary to install a single phase capacitor at E having a 60 cycle reactance of 54 ohms. If voltage correction is necessary on the two phase tap from E, the size of the required capacitors may be calculated in the same manner.

The voltage gradient can now be represented by Fig. 3.

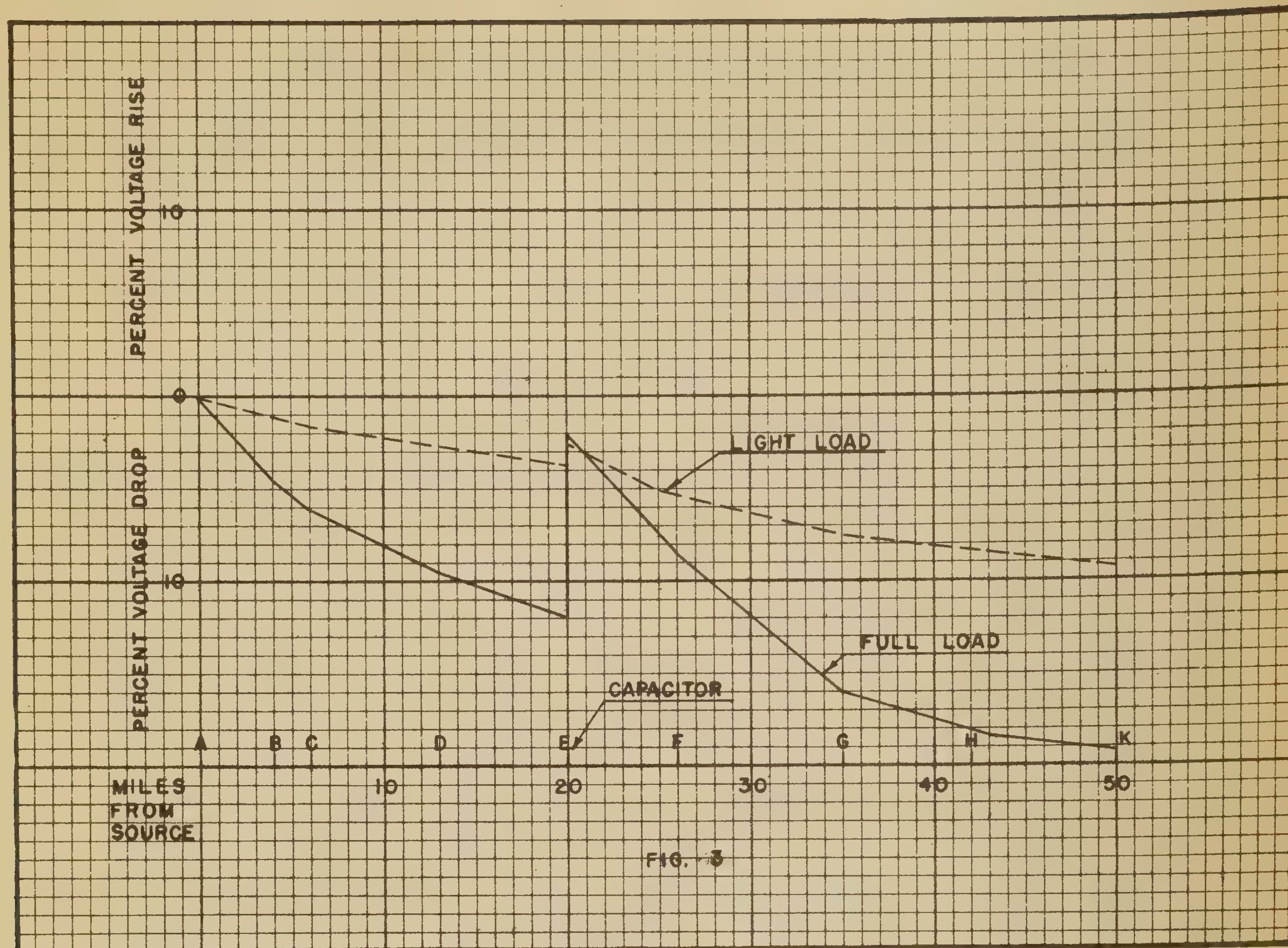

FIG. 3

Examination of Fig. 3 shows that maximum variation at any point on the line is 10%. The choice of location is therefore in order. But a location closer to the source such as at B or C may have provided better regulation along the whole system. Fig. 4 illustrates the effect of placing the capacitor at C.

Calculation:

Distributed full load between C & E = 2 x 14 = 28 kva
Taps D & E (full load) = 175 kva
Taps F, G, H, K - single phase (full load) = 85 kva
Distributed full load on single phase tap EK = 1/3 x 2 x 30 = 20 kva

$K_L = 1/3 \times (28 + 175 + 85 + 20) = 102.7$ kva

$\theta = 41.4$ degrees
$\sin \theta = 0.66$
$V = 10\%$
$\theta_N = 26.2$ degrees

$\sin \theta = 0.44$
$E = 7.2$ kilovolts

Distributed light load between C & E = 1/2 x 14 = 7 kva
Taps D & E (light load) = 40 kva
Taps F, G, H, K - Single phase (light load) = 15 kva
Distributed light load on single phase tap EK = 1/3 x 1/2 x 30 = 5 kva

$$K_N = 1/3 \times (7 + 40 + 15 + 5) = 22.3 \text{ kva}$$

$$X_C = \frac{10\ E^2\ V}{K_L \sin\theta} = \frac{10 \times 7.2^2 \times 10}{102.7 \times 0.66} = 76.6 \text{ ohms}$$

$$V_N = \frac{K_{LN}\ X_C \sin\theta_N}{10\ E^2} = \frac{22.3 \times 76.6 \times 0.44}{10 \times 7.2^2} = 1.5\%$$

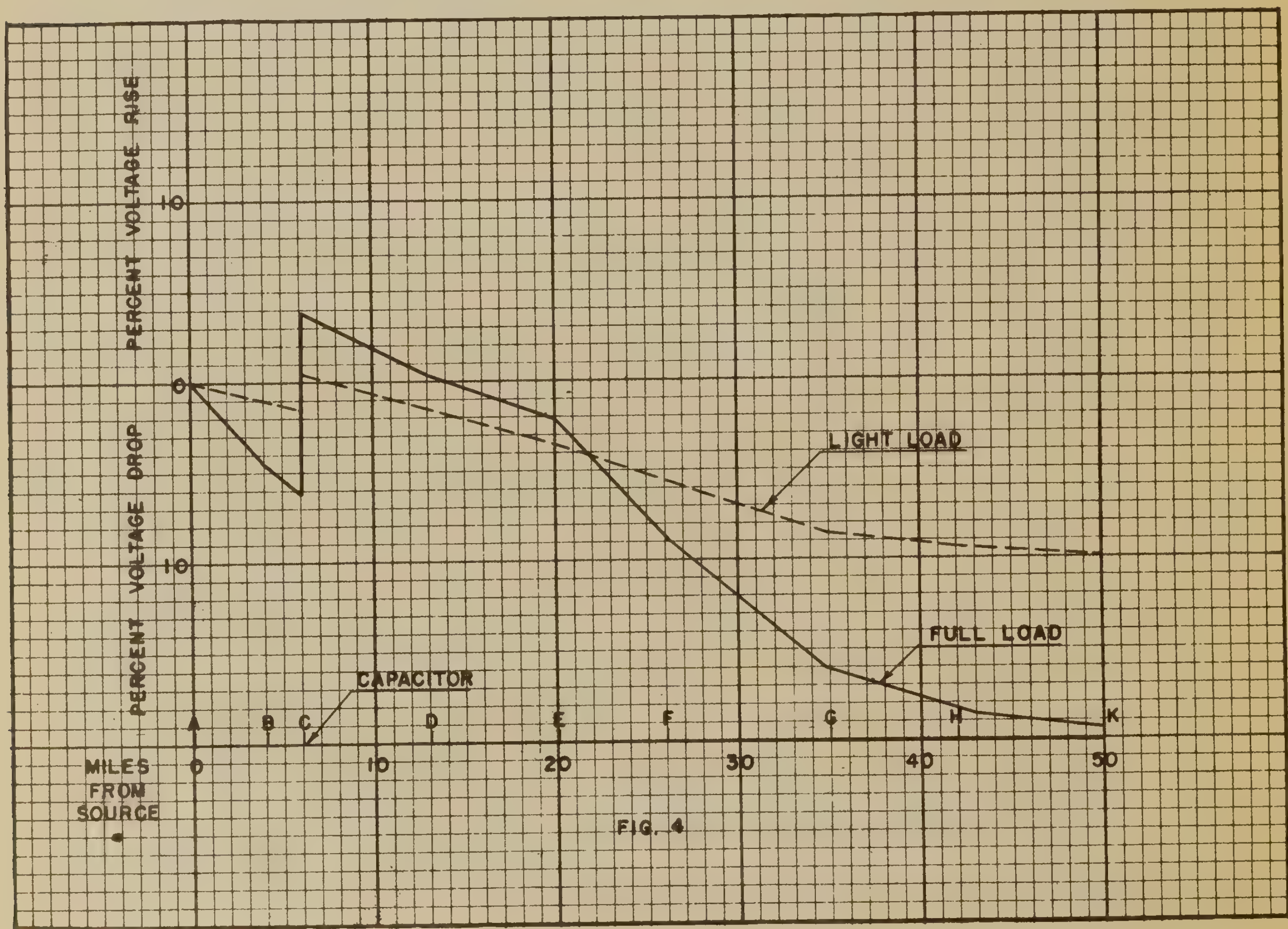

Figure 4 indicates that installation of the capacitor at C would improve regulation between the substation and point F, since the maximum variation between these points would now be under 5% instead of 9% as indicated in Fig. 3.

However, it should be noted that this better regulation is obtained at an increase in capacitor cost, and unless the loads between the substation and point E require this closer regulation the additional cost would be unwarranted.

Since the reactance of a capacitor is given by:

$$X_C = \frac{1}{2\pi f C} \qquad (3)$$

where: f = frequency in cycles
C = capacity in farads

then: $$C = \frac{1}{2\pi f X_C} \qquad (4)$$

and the capacitance needed for 22.6 ohms reactance is approximately twice that required for 54 ohms (the reactance required for installation at E).

III. VOLTAGE RATING OF SERIES CAPACITORS.

A. Line to Ground Voltage Rating

The insulation to ground of the series capacitor should be coordinated with line insulation. In general, the potential between the capacitor terminals and ground will be greater than the voltage drop across the capacitor itself. Standard capacitors can be mounted on insulators rated at line voltage, or specially built capacitors can be obtained having the proper insulation between terminals and case. The choice between these two types will depend on cost and ease of mounting. It will usually be found more economical to mount standard capacitors on insulators but, from the standpoint of safety, a grounded case is more satisfactory despite the higher cost.

B. Terminal to Terminal Voltage Rating

The voltage drop across the capacitor is dependent on its reactance and on the load current flowing through it. In order to determine the terminal to terminal voltage rating the following information is required:

1. Full load line current

2. Peak line currents due to motor starts

3. Maximum short circuit current through the capacitor

Momentary voltage rise of 150% of the nominal rating is permissible on series capacitors. The terminal to terminal voltage rating may be based either on peak current due to motor starts or on maximum short circuit current. The choice between these two will be dictated by considerations of economy. If the peak line current is used, then it may be necessary to provide automatic shorting switches to by-pass the capacitor on short circuits. On the other

hand, calculation of rating on the basis of the maximum short circuit current may require a higher capacitor rating. The cheapest of these two methods will be the one to be used. The terminal to terminal voltage rating is determined by use of the following formulae:

$$V_P = X_C \ I_p \qquad (5)$$

where: V_P = Voltage rating for instantaneous peak currents

X_C = Capacitor reactance (ohms)

I_p = Peak line current (either due to motor starts or to short circuit)

then: $$V_S = \frac{V_P}{1.5} = 0.67\ V_P \qquad (6)$$

where V_S = Voltage rating of the series capacitor

IV. PROTECTION OF SERIES CAPACITORS

A. External Short Circuit Protection

If the maximum short circuit current is greater than I_p a protective device must be installed to by-pass the short circuit current around the capacitor. Since this protective device must act within the first two cycles following the short circuit, it is evident that no mechanical device is feasible. A gap which will limit the voltage across the capacitor to 250% of its rated voltage is therefore recommended. However, where the line short circuit protection is slow some automatic switching arrangement may be necessary in conjunction with the gap in order to short out the capacitor after the first few cycles and for the duration of the short-circuit current flow, to prevent the gap from carrying the short circuit current. When the ratio of system reactance to resistance is high, it is of major importance to provide this shorting equipment, since with the system reactance cancelled out by the series capacitor the short circuit current may exceed the rating of the sectionalizing devices on the line.

B. Internal Short Circuit Protection

If the dielectric in the capacitor should break down causing a short between the capacitor terminals, ordinarily no damage to line equipment would result and the line current would be unchanged provided no short to the grounded case occurred. However, where the capacitor is one of a bank on a multiphase line, continued operation of the bank with one capacitor shorted may cause failure of the other capacitors in the bank. It is, therefore, advisable to provide for automatic shunting out of the bank in case of an internal dielectric fault.

C. Lightning Protection

Where the capacitor case is insulated from ground, no additional lightning protection is required, since the capacitor offers low impedance to high frequency surges and is, consequently, self-protecting between terminals. Where the case is grounded or not mounted on insulators lightning arresters connected line to ground should be used for protection. Arresters should also be used on large capacitor installations with shorting equipment for overload protection.

V. EFFECT OF SERIES CAPACITORS ON INDUCTION MOTORS AND SYNCHRONOUS MACHINES

The introduction of a series capacitor may sometimes cause "self-excitation" of induction motors supplied by the line. This can be eliminated by shunting the capacitor with a high resistance. The loss introduced by such a resistance is generally less than 10 percent of the line loss. However, the "self-excitation" of induction motors on distribution circuits due to series capacitance is a rare condition, since the existence of other loads between the capacitor and induction motor produces the same effect as shunting the capacitor with a resistance. The judicious location of the capacitor so that some load intervenes between it and the induction motor can nearly always prevent "self-excitation". In general, when the capacitive reactance is less than one-half the system short-circuit reactance "self-excitation" will not occur for a normally loaded induction motor.

In the case of synchronous machines "hunting" may result. This can be either eliminated or reduced by proper location of the capacitor. Conditions for proper location and methods for their determination are beyond the scope of this bulletin. The manufacturer should be consulted for this information when capacitor installations are planned on a system including synchronous machines.

VI. TYPES OF SERIES CAPACITORS AVAILABLE.

Four classes of series capacitors are available, depending on type of protection incorporated.

Class I - No protection
Class II - Short circuit protection
Class III - Short circuit and dielectric fault protection
Class IV - Short circuit, dielectric fault, and overload protection

VII. LIMITATION ON THE USE OF THE SERIES CAPACITOR.

It should be noted that series capacitor constants, once calculated on the basis of a set of assumed circuit and load conditions, will operate properly only when those conditions exist. When load conditions change appreciably, it may be necessary to recalculate and change the capacitor installation.

In general, series capacitors are not recommended for use when the minimum system power factor exceeds 85 percent.

APPENDIX

Derivation of Formula for KVA Rating of Series Capacitor

X_C = capacitive reactance in ohms

e = line volts rise due to the capacitor

$$e = IX_C \sin\theta \text{ (approximately)} \qquad (7)$$

$$\text{or } X_C = \frac{e}{I \sin\theta} \qquad (8)$$

V = % voltage rise across capacitor
K_L = kva of load (per phase)
E = Phase to neutral voltage of system (kilovolts)

$$e = 10\,EV \qquad (9)$$

$$I = \frac{K_L}{E} \qquad (10)$$

Substituting (9) and (10) in (8)

$$X_C = \frac{10\,E^2\,V}{K_L \sin\theta} \qquad (11)$$

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